Thin-film coatings

OSLO coating library

Optical thin films have numerous scientific, technological, and commercial applications over a wavelength range that extends from the x-ray to the submillimeter regions. They can be used to shape the spectral response of the light transmitted and reflected by the surfaces to which they are applied. Some of the generic spectral filters that are made of multilayer coatings include antireflection coatings, neutral beam splitters, reflectors, short- and long wavelength cut-off filters, narrow band transmittance filters, and polarizers. To achieve these effects, from one to many tens of layers may be required. From the point of view of a lens designer the most important filter types are antireflection coatings and reflecting coatings. However, there may be instances where it may be of interest for lens designers to perform preliminary order of magnitude calculations with some of the other types of multilayer coatings mentioned above. For this purpose a number of filter designs have been added to OSLO.

The multilayers can be constructed of dielectric layers only, or they can consist of a combination of both metallic and dielectric layers. With all-dielectric layer systems the incident light is either transmitted or reflected—there are no absorption losses. Furthermore, because the dispersion of the refractive indices of dielectric materials is relatively small, the spectral features can be tuned over a wide range of wave-lengths simply by scaling the thicknesses of all the layers by the same amount. This is true only if the new position of the spectral feature of interest lies within the transparency range of the coating materials. Furthermore, for a given angle of incidence and plane of polarization, the transmittance T and the reflectance R of an all-dielectric layer system are independent of the direction of the incident light and they obey the relation $T + R = 1.0$.

If there are absorbing films in the multilayer system, some of the light incident on the multilayer will be absorbed . The condition $T + R + A = 1.0$ holds, where A represents the absorbtance. The scaling of the layer thicknesses in order to shift the features in the spectrum is no longer so simple. First, the dispersion of the optical constants of metals are much more pronounced than that of dielectric coating materials. Second, because the extinction coefficients of metals are large, the changes in the thicknesses of the metal layers must be much smaller. Lastly, whilst the transmittance of a multilayer coating with absorbing layers is independent of the direction of the incident light, in general this is not true for the reflectance and absorbtance.

The properties of both all-dielectric and metal-dielectric layer systems depend on the angle of incidence and on the state of polarization of the incident light. In general, the spectral features of multilayer coatings shift towards shorter wavelengths with an increasing angle of incidence. In addition, for angles of incidence greater than 10 or 15 degrees, a marked polarization splitting can usually be observed. For unpolarized light this results in a general broadening of the spectral features. This has important implications for lens designers. For best results, any filter in which there are sharp transitions from high to low transmittance or reflectance should be located within that part of a lens system in which the angles of incidence and the convergence angles are as small as possible.

Coating material considerations

The optical constants of thin films can depend on the actual process used for their deposition. Films produced by thermal evaporation and by conventional electron beam gun evaporation can be quite porous. Although heating of the substrate can result in a reduction of the porosity, it rarely results in completely dense films. The spectral features of coatings produced in this way frequently shift towards longer wavelengths as water vapor is adsorbed by the pores. For some applications it is possible to predict sufficiently accurately the changes that will occur on exposure of the multilayer to the atmosphere. For other, more stringent applications, it is necessary to produce very stable multilayer systems that do not age at all with time and exposure to moisture. Higher energy deposition processes, such as ion assisted electron beam gun evaporation, ion plating, ion sputtering or magnetron sputtering, yield dense coatings that meet these requirements. However, either the equipment is more expensive, or the deposition process is slower and so, as a rule, a premium has to be paid for such coatings.

Dielectrics can be classified into soft and hard coating materials. The former can be deposited by thermal evaporation at relatively low temperatures and are frequently protected by a cemented cover glass from damage due to abrasion. Hard coating materials are deposited by electron beam gun evaporation, or by sputtering. They are much harder and are quite suitable for front surface mirrors.

The optical properties of metals are even more sensitive to the deposition process than those of dielectric layers. This is especially true for partially transparent metal layers used in beam splitters and in certain advanced multilayer coatings.

The conclusion from the above is that, until a deposition process is decided upon, it is difficult to predict what optical constants should be used for the design of the multilayer. It is customary to use approximate optical constants for preliminary designs. Although it is frequently sufficient for this purpose to use non-dispersive refractive indices for the dielectric layers, the dispersion of the optical constants of metals must be taken into account. A good source of information on the optical constants of metals is the “Handbook of Optical Materials” vols. I, II edited by Palik [1,2]. Any systems designed in this way will require only slight modifications of the thicknesses of the layers to allow for the discrepancy between calculated and experimental optical constants.

Some sample multilayer systems

Some of the multilayer systems presented below are based on multiples of quarter wave layers which are easy to monitor by optical means. These systems are best represented by a notation in which H and L correspond to high and low refractive index layers of quarter wave optical thickness, respectively. Thus, for example, (HL)^2 H is the same as HLHLH, which represents a five layer quarter wave stack. (HL)^3 (LH)^3 is the same as HLHLH2LHLHLH, which represents an eleven layer narrow band filter in which the central layer is a half wave layer of low refractive index, etc.

Other systems consist of layers with thicknesses that depart from quarter wave thicknesses significantly. The additional degrees of freedom available in such refined systems can be used to optimize the performance of the multilayer. The thicknesses of such layers are frequently monitored using quartz crystal monitors.

The all-dielectric multilayer systems listed in the table below, with the exception of two systems, are constructed out of two coating materials only with non-dispersive refractive indices 1.45 and 2.35. These values are not too far removed from the refractive indices of the soft coating material pair MgF2 and ZnS or from the hard coating material pair SiO2 and Nb2O5. The optical constants of aluminum were taken from Palik. Inconel alloy constants were measured at NRCC. The substrate and incident medium materials in all systems are BK7 glass or air. M in system 2 stands for a quarter wave layer of medium refractive index of 1.7.

No.	Name	Type	Layers	Description
1	AR_1	single layer MgF2 AR coating	1	glass/L/air
2	AR_2	quarter-half-quarter AR coating	3	glass/M2HL/air
3	AR_3	narrow band AR coating	2	glass/optimized/air
4	AR_4	wide band AR coating	7	glass/optimized/air
5	R_1	quarter wave stack reflector	13	glass/(HL)^6 H/air
6	R_2	opaque Al layer reflector	1	opaque Al /air
7	SP_1	short wavelength pass filter	17	optimized, between glass
8	LP_1	long wavelength pass filter	17	optimized, between glass
9	BS_1	Inconel layer beam splitter	1	0.0125 µm of Ag cemented between two 45 deg prisms
10	BS_2	multilayer beam splitter	7	optimized, between two 45 deg prisms of BK7 glass

11	NB_1	narrow band filter (1 cavity)	15	glass/(HL)^4 (LH)^4 /glass
12	NB_2	narrow band filter (2 cavities)	31	glass/optimized/glass

A more detailed explanation of the theory of optical thin films will be found in the excellent book by Macleod [3]. For more information on classical and less usual applications of optical thin film coatings the interested reader is referred to references [4,5].

References

1. E. D. Palik, Handbook of Optical Constants of Solids I (Academic Press Inc., Orlando, 1985).

2. E. D. Palik, Handbook of Optical Constants of Solids II (Academic Press Inc., Boston, 1991).

3. H. A. Macleod, Thin Film Optical Filters (McGraw Hill, New York, 1986).

4. J. A. Dobrowolski, “Optical Properties of Films and Coatings,” in Handbook of Optics (Editor-in-Chief,. M. Bass) (McGraw-Hill, New York, 1995), pp. 42.1-42.130.

5. J. A. Dobrowolski, “Usual and Unusual Applications of Optical Thin Films-An Introduction,” in Thin Films for Optical Coatings (Eds. R. F. Hummel and K. H. Guenther) (CRC Press, Inc., Boca Raton, Florida, 1995), pp. 5-35.